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# RELIABILITY OF DEFECT DETECTION IN WELDED STRUCTURES

P.F. Packman (1)
J.K. Malpani (2)
F. Wells (3)
B.W.E. Yee (4)

1) Professor, 2) Graduate Student and 3) Assn't Professor
Vanderbilt University, Nashville, Tn. 37235

4) Convair Aerospace, General Dynamics Div.
Ft. Worth, Tx. 76101

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An analysis has been made of the ability of several nondestructive inspection procedures to reliably detect surface fatigue cracks. It is shown that the ability of penetrant systems of aluminum and titanium are over 90% for cracks whose surface length is greater than 0.939mm (0.037 inches) in length and decreases for cracks less than this value. The probability of detection of these cracks, given that the crack is present has been determined at 90, 95, and 99% confidence factors. The conditional probabilities associated with an error call have also been developed. For this analysis ~~four~~ (4) outcomes were defined: ~~as follows~~ (Cont on 1473 A)

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Ft. Worth, Tx. 76101

## NOMENCLATURE

| | |
|---|---|
| $a$ | Flaw Depth (inches) mm |
| $\alpha$ | Quality index ratio |
| $1-\alpha'$ | Confidence Probability |
| $\beta$ | Error Probability ratio |
| $c$ | Flaw Length on Surface (inches) mm |
| $\gamma$ | Success Probability ratio |
| $n$ | Number of Tests |
| $P$ | True Probability of Detection |
| $\bar{P}$ | Natural Estimate of P (Sn/n) |
| $P'$ | Lower Bound for P (Probability of Detection at Given Confidence Level) |
| $P(A)$ | Probability of a Flaw Indication |
| $P(A')$ | Probability of No Flaw Indication |
| $P(B)$ | Probability that a Flaw of a Given Size Exists |
| $P(B')$ | Probability that a Flaw of a Given Size does not Exist |
| $S_n$ | Number of Detections of Flaws in the Tests |
| $Z$ | Standardized Normal Variable |
| $Z_\alpha$ | Tabulated Standard Normal Variable for $1-\alpha'$ Confidence Probability |

## ABSTRACT

An analysis has been made of the ability of several non-destructive inspection procedures to reliably detect surface fatigue cracks. It is shown that the ability of penetrant systems of aluminum and titanium are over 90% for cracks whose surface length is greater than 0.939mm (0.037 inches) in length and decreases for cracks less than this value. The probability of detection of these cracks, given that the crack is present has been determined at 90, 95, and 99% confidence factors. The conditional probabilities associated with an error call have also been developed. For this analysis four outcomes were defined as follows:

1. The detection of a crack that is present, 2. The missing of a crack that is present, 3. The detection of a crack that does not exist (false call) and 4. The verification that a part does not contain a flaw. Using Bayes Theorm, the conditional probabilities have been established in terms of a material quality factor, an error probability ratio and a success probability ratio. The results of two inspectors, one with a 6% error probability, and the other with a 36% error probability have been examined.

## INTRODUCTION

The objective of a nondestructive inspection process is to determine the presence of or absence of flaws in the part that is inspected. It is immediately obvious that each NDI procedure has limitations as to the ability of that technique to find small flaws. Because of the need for increasing the reliability of structural parts, there has developed an increasing reliance on the extensive application of NDI to ensure freedom from all flaws. Thus, the trend has been to improve the NDI process to find smaller and smaller flaws within the material.

With the adaption of a fracture mechanics design process for critical components, the size of the largest flaw that must be detected (and hence removed from the component) can be quantified (1, 2). In order to incorporate the NDI sensitivity into the design process, the ability of each inspection technique to find flaws of varying sizes must also be determined quantitatively (3). This has been determined for a limited number of NDI processes and for a limited number of materials It is important to recognize that with this quantification of NDI sensitivity, there is associated a statistical distribution function. This means that there is no absolute guarantee of finding or missing a defect in a single NDI observation, but only a probability of success with a given confidence value.

The probability of detection of a crack in a specimen is defined to be the probability that a trained inspector will verify the presence of the crack during a given inspection process. The inspection process is the total sequence of steps

used in verifying the presence or absence of the defect. For example for a penetrant inspection this includes; precleaning, application of penetrant, dwell time, penetrant removal, application of developer, examination of the specimen and cleaning.

The probability of detection at a given confidence level, P', guarantees with the degree of confidence that a crack will be detected with the stated probability. If Sn is the number of detections of flaws in n tests, $S_n$ has a binomial distribution with mean nP and variance nP(1-P). A natural estimate of P, called $\bar{P}$ is the ratio $S_n/n$, the sample proportion of detections of cracks in the total number of tests. The main interest is to find P', a lower bound for P with a stated degree of confidence, say 95 or 99%.

When the value of n is less than 50, the exact binomial distribution is used, and standard tables are available (4). For large n and small P (close to zero or 1-P close to unity) the Poisson distribution can be used to find the lower bound. The Poisson parameter is equal to nP'. For large n and 0.1 $\bar{P} \leq 0.9$, a normal approximation to the binomial is used. The standardized normal variable $Z = (Sn - nP)/\sqrt{nP(1-P)}$ is approximately distributed as a standard variable.

Hence:

$$P(S_n > nP - Z_\alpha \sqrt{nP(1-P)} = 1- \alpha' \qquad (1)$$

A further approximation of substituting $\bar{P}$ in nP(1-P) may be used instead of solving the quadratic inequality, which gives a lower and an upper bound for P.

## FLAW DETECTION PROBABILITIES

In tables I, II, and III the range detection probabilities have been obtained for several inspection processes.(5) This measures the probability of detection of flaws within a given flaw size range. In all of these tests, the flaw was a surface fatigue crack of elliptical shape. If sufficient inspections have been made within each flaw size range, the confidence levels can be high with the associated high degree of success of finding a flaw. If however, the number of observations is low, the detection probabilities are low to maintain the required degree of confidence. This was the procedure used for most of the NDI demonstration programs. The major problem in obtaining sufficient numbers of observations in each flaw size range is that it is not known apriori how many of each flaw size will be inspected, and certain critical ranges may not have sufficient numbers of inspections to obtain the desired probability of detection. In all of our data the exact binomial or Poisson was used rather than equation 1.

In tables IV, V, and VI, the same data has been reevaluated in terms of the cumulative detection probabilities. This measures the probability of detecting a flaw of the stated size or greater. Thus, a cumulative detection probability biases the results in favor of the large flaws, providing that no large flaw is missed. If a large flaw has been missed, and smaller flaws are not missed, this procedure penalizes all of the smaller flaw observations. However, this is consistant with the

fracture mechanics approach which considers the larger flaws to be much more important to the premature failure of the structure. It can be seen by comparing the results that for most flaw sizes, the cumulative probabilities are are higher than the range probabilities due to the larger number of observations. The cumulative results tend to fall off at larger flaw sizes due primarily to the decreasing numbers of observations. For the steel magnetic particle inspection, it is due to the fact that two flaws were missed in the large flaw size range but none were missed in the intermediate ranges.

This data assumes that there are only two outcomes for each observation; 1) either a crack is found, or 2) a crack is missed. In the actual situation there are actually <u>four</u> outcomes to each observation:

1. The detection of a crack that is present
2. The missing of a crack that is present

as well as

3. The detection of a crack that does not in fact exist ( a false indication)
4. The non-detection of a crack that does not exist. (this states correctly that a part does not contain a flaw)

Of particular interest is item 3. This implies there is a finite possibility that the NDI process will (wrongly) call out that there exists a part containing a defect, when in fact there is no defect present. The detection probabilities obtained in tables I to VI do not take into account any observations made on unflawed specimens; the only consideration for probability of detection here is the estimate $S_n/n$, where the total number of tests n is the total number of specimens inspected that contain

defects.

## DEALING WITH ERROR CALLS

In a typical nondestructive inspection program, a large proportion of the specimens that are inspected for defects are "dummy" specimens. This means that they do not have defects present in the specimen, but are inspected along with the flawed specimens so that the expectation value of the inspector is low. In the real world situation where the inspector does not expect to find a large number of flawed specimens, it is important that the flaw indication be clearly visible and above the general level of the random indications. A difficulty arises when the NDI process is improved so as to increase the sensitivity or ability of the technique to find small flaws.

When the detection sensitivity is increased by a technique such as increasing the gain for a pulse echo ultrasonic inspection, a large number of indications may be obtained that do not correlate with actual flaws. These are called "squacks" and can seriously affect the outcome of the inspection.

Consider the following situation. Two NDI inspection procedures are to be evaluated for use. The results of an inspection procedure gives:

Method I finds 29 out of 29 flawed specimens and calls 5 of 30 specimens that do not contain flaws as having flaws.

Method II finds 29 out of 29 flawed speciemns and calls 15 out of 30 specimens that do not contain flaws as having flaws.

By the statistic outlined in the earlier section, both techniques exhibit at least a 90% probability of detection with a 95%

confidence level. It is obvious that in actual use, method II would be much more expensive, since it results in more errors in order to achieve the same probability of detection. These false indications would result in more time spent evaluating the wrong data.

To account for the possibility of wrong calls requires the use of conditional probabilities. Let P(B) be the probability that the flaw of a certain size exists. The probability that the flaw does not exist is P(B') and is given by 1-P(B). Similarly, in the inspection process, let P(A) be the probability that a flaw is indicated, irrespective of whether the flaw does exist or not, and the probability that the flaw is not indicated is P(A') given by 1-P(A). Then the possible outcomes to an inspection process can be given as:

P(A/B) = the probability that a flaw is indicated given that the flaw exists in the part.

P(A'/B) = the probability that a flaw is not indicated given that the flaw exists P(A'/B) = 1-P(A/B)

P(A/B') = the probability that a flaw is indicated given no flaw exists in the part

P(A'/B') = the probability that no flaw is indicated given no flaw exists (the verification of the part as being flaw free P(A'/B') = 1-P(A/B')

CONDITIONAL PROBABILITIES FOR DETECTION

The four outcomes can be represented by a Venn diagram as shown in Figure 1. For the analysis we are interested in the reversed conditions, i.e. the probability that there is a flaw present given that it is indicated. Using Bayes theorm we can

calculate the following conditional probabilities:

$P(B'/A')$ = the probability a flaw does not exist, given a flaw is not indicated

$$= \frac{P(B')P(A'/B')}{P(B)P(A'/B) + P(B')P(A'/B')} \tag{2}$$

$P(B/A')$ = the probability a flaw exists given a flaw is not indicated

$$= \frac{P(B)P(A'/B)}{P(B)P(A'/B) + P(B')P(A'/B')} \tag{3}$$

$P(B'/A)$ = the probability a flaw does not exist given a flaw is indicated

$$= \frac{P(B')P(A/B')}{P(B')P(A/B') + P(B)P(A/B} \tag{4}$$

$P(B/A)$ = the probability a flaw exists given a flaw is indicated

$$= \frac{P(B)P(A/B)}{P(B')P(A/B') + P(B)P(A/B)} \tag{5}$$

Equation 4 describes the conditional probability associated with wrong indications of flaws, while Equation 5 describes the probability associated with the detection of a flaw and the flaw actually being present. These can be simplified by considering the following ratios:

$$\text{Let } \alpha = \frac{P(B')}{P(B)} = \frac{P(B')}{1-P(B')} \tag{6}$$

$$\beta = \frac{P(A/B')}{P(A/B)} \tag{7}$$

$$\gamma = \frac{P(A'/B')}{P(A'/B)} = \frac{P(A'/B')}{1-P(A/B)} \tag{8}$$

Equations 2-5 become:

$$P(B'/A') = \frac{1}{1+\frac{1}{\alpha\gamma}} \tag{9}$$

$$P(B/A') = \frac{1}{1+\alpha\gamma} \tag{10}$$

$$P(B'/A) = \frac{1}{1+\frac{1}{\alpha\beta}} \tag{11}$$

$$P(B/A) = \frac{1}{1+\alpha\beta} \tag{12}$$

## QUALITY INDEXES

### Estimation of Probability Ratios

The term $\alpha$ is a quality index for a material and refers to the ratio of probability that a flaw does not exist P(B') to the probability that a flaw does exist in a material P(B). No specific information can be given regarding the magnitude of $\alpha$ , but it is apparent that it could be a measure of quality of a material or the quality of a weld. There are two methods by which the value of $\alpha$ can be estimated. First consider the quality index to be a measure of how close the defect free strength corresponds to the average strength of the material. This assumes that the variability in actual strength level is caused by the presence of defects. Hence, for a material whose strength level corresponds to an "A" value of strength (90/95) the value of $\alpha$ would be 9.0.

Another, perhaps more accurate method of determining $\alpha$ , would be to examine the defect-size distribution curve for the alloy under investigation. The actual defect size histogram would have to be determined by careful metallographic examination and quantitative metallographic techniques. The value of

$\alpha$ would be determined by the ratio of the total number of defects observed to the number of defects observed within the particular flaw size. Size distribution curves of defects in forged alloys of this nature have been developed by L.S. Fel' dman (7) for USSR Aluminum alloy W-93 shown in Figure 2. The Figure 3 curve shows the calculated values of $\alpha$ .

Error Probability Ratio

The $\beta$ term is the ratio of the probability that a flaw is indicated, given no flaw exists P(A/B') to the probability a flaw is indicated given a flaw exists P(A/B) i.e. the ratio of the wrong call probability to the demonstrated probability of detection. A good NDI technique should have a low value of $\beta$ . For simplicity sake this term will be called the "error probability ratio".

Success Probability Ratio

The $\gamma$ term is the ratio of the probability that a flaw is not indicated given no flaw exists P(A'/B') to the probability that a flaw is not indicated given a flaw exists P(A'/B i.e. a measure of the ratio of the probability of correct calls to the value of the probability of missing a flaw in the demonstration (since P(A'/B) = 1-P(A/B). A good NDI technique should have a high measure of $\gamma$ . This term can be called the "success probability ratio".

Conditional Flaw Detection Values

Table VII shows the influence of the structural quality factor $\alpha$ , on the value of P(B/A) or the probability the flaw

exists given the fact that a flaw is indicated. We have assumed two values of error probability ratio $\rho$ , to be 0.05/0.95 and 0.005/0.95. The first corresponds to an inspection process for which 5% of the flaws indicated are false, the second indicates that 0.5% of the flaws indicated are false. For the first value of $\rho$ with a quality factor of 9 the probability of the existance of the flaw is 68%. If however, the probability of error calls decreases to 0.5% the probability of existance of the flaw given the indication increases to 95%. It should be recognized that these are not the actual measures of the ability of the NDI technique to detect a flaw of a given size. This measures only the probability that the flaw exists given the fact that the flaw has been detected. These terms, P(B/A) should be multiplied by the factor that measures the true probability of the flaw being detected, given the flaw is present as in Tables I to VI.

Given a value of flaw detection capability of a technique such as aluminum penetrant to detect flaws in the range 0.089 - 0.1149 inches long (2.26 - 2.92 mm) to be 96.8% at a 90% confidence factor, with a quality index of 9, the true probability of a flaw being present once the NDI technique has found an indication would be (0.968 x 0.68) or 65% if the technique had a 5% error probability but (0.968 x 0.95) or 91% if the error probability was only 0.5%.

Table VIII evaluates the influence of the percentages of false indication on the actual value of detection capabilities of a particular NDI technique. We assume that the probability of detection given a flaw is present is either 90% or 95% ( at some given confidence level as obtained for some flaw size during a

demonstration program). The percentage of false indications is allowed to assume the values of 0.1%, 0.2%, 0.5%, 1.0%, 5.0%, 10% with the quality index kept constant at $\alpha = 10$. Table VIII shows that false indications less than 1% of the total indications have only a minor influence on the actual probability of a flaw existing in the part given a flaw is indicated. If the percentage of false indications exceeds this value, the false indication percentage becomes the major dominating factor in determineing the actual ability of the NDI procedure to correctly identify flaws. Thus, even though the detection probability of small flaws may be 90% based only on the correct identification of flaws in a flaw size range if the NDI process indicates that 5% of the time it finds a false indication, the actual probability of there being a flaw of this size in the real world is only 57%. This clearly places a heavy burden on NDI researchers to develop highly reliable techniques with small amounts of false indications.

Reliable NDI data is difficult to determine since a great deal of nondestructive inspection does not keep the procedure the same. If a number of defects, known to be present, are missed by a particular NDI process the test is usually terminated. The NDI procedures are reexamined and improved rather than complete the original test and report the results. Some limited data on penetrant inspection of titanium alloy 6AL-4V STA including false indication percentages can be found in reference (9). The data is evaluated in Table IX. Two inspectors are evaluated, one inspector finds 36% false indications, one inspector finds only 6% false indications. It should be noted that the value of 94%

probability of detection for the 0.10 inch to 0.25 inch cracks has been reduced to 19.4% and 57%. Clearly inspector II who finds the same number of defects as inspector I, but does so without the large number of false indications has the higher probability of the defect being present given the indication.

## INFLUENCE OF HUMAN FACTORS

In closing, one point should be made. In our analysis we have assumed that the percentage of false indications is constant, independent of the flaw size range being investigated. This need not be true in actual practice. One is led to believe that the percentage of false indications would increase as smaller flaws are sought. It is unlikely that a false indication percentage of 30% would be common for all flaw sizes independent of the actual flaw size range. If the operator were aware of the range of flaw sizes that he was looking for, the percentage of false indications should be much smaller. However, in a normal NDI demonstration program, where the flaw size ranges are deliberately mixed so as to ensure that all flaws have equal probability of being within the inspection population, one must assume correctly that there would be little variation in false indication percentage.

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TABLE 1

RANGE PROBABILITY OF DETECTION ALUMINUM PENETRANT

| Flaw Size Range in mm (inches) | Number of Observations | Number of Misses | Probability of Detection at Confidence 90% | 95% | 99% |
|---|---|---|---|---|---|
| 0.942 - 1.1125 (0.0371-0.0438) | 9 | 2 | 0.51 | 0.45 | .345 |
| 1.1125 - 1.526 (0.0438-0.0601) | 34 | 0 | 0.935 | 0.916 | 0.873 |
| 1.526 - 2.260 (0.0601-0.0890) | 42 | 0 | 0.947 | 0.931 | 0.896 |
| 2.260 - 2.918 (0.0890-.1149) | 72 | 0 | 0.9685 | 0.959 | 0.938 |
| 2.918 - 4.922 (.1149-0.1938 | 86 | 0 | 0.973 | 0.965 | 0.947 |

TABLE II

RANGE PROBABILITY OF DETECTION TITANIUM PENETRANT

| Flaw Size Range in mm (inches) | Number of Observations | Number of Misses | Probability of Detection at Confidence 90% | 95% | 99% |
|---|---|---|---|---|---|
| 0.2032-0.4826 (0.008-0.019) | 19 | 7 | .450 | .420 | .345 |
| 0.4826-0.939 (0.019-0.937) | 55 | 7 | .786 | .761 | .709 |
| 0.939-1.397 (0.037-0.055) | 60 | 0 | .962 | .951 | .926 |
| 1.397 1.709 (0.055 0.0673) | 65 | 0 | .965 | .955 | .932 |
| 1.709-2.827 (0.0673-0.1113) | 196 | 0 | .976 | .969 | .953 |
| 2.827-6.35 (0.1113-0.2500) | 134 | 0 | .983 | .976 | .966 |

TABLE III

RANGE PROBABILITY OF DETECTION STEEL MAGNETIC PARTICLE

| Flaw Size Range in mm (inches) | Number of Observations | Number of Misses | Probability of Detection at Confidence 90% | 95% | 99% |
|---|---|---|---|---|---|
| .8204-1.038 (0.0323-0.0409) | 5 | 3 | 0.106 | 0.077 | 0.035 |
| 1.038-2.034 (0.0409-0.0801) | 39 | 7 | 0.715 | 0.689 | 0.635 |
| 2.034-2.286 (0.0801-0.0900) | 52 | 0 | 0.957 | 0.944 | 0.915 |
| 2.286-4.130 (0.0900-0.1626) | 70 | 0 | 0.968 | 0.958 | 0.936 |
| 4.130-5.753 (0.1626-0.2265) | 49 | 2 | 0.895 | 0.875 | 0.84 |

TABLE IV

CUMULATIVE PROBABILITY OF DETECTION ALUMINUM PENETRANT

| Flaw Size in mm (inches) | Cumulative Number of Observations | Cumulative Number of Misses | Probability of Detection at Confidence 90% | 95% | 99% |
|---|---|---|---|---|---|
| .953 (0.0371) | 243 | 2 | .978 | .974 | .965 |
| 1.526 (0.0601) | 200 | 0 | .989 | .985 | .977 |
| 2.154 (0.0848) | 174 | 0 | .987 | .983 | .974 |
| 3.185 (0.1254 | 74 | 0 | .969 | .960 | .940 |

TABLE V

CUMULATIVE PROBABILITY OF DETECTION TITANIUM PENETRANT

| Flaw Size Greater than in mm (inches) | Cumulative Number of Observations | Cumulative Number of Misses | Probability of Detection at Confidence | | |
|---|---|---|---|---|---|
| | | | 90% | 95% | 99% |
| .4826 (0.019) | 410 | 7 | .971 | .968 | .961 |
| .9398 (0.037) | 355 | 0 | .993 | .991 | .987 |
| 1.397 (0.0550) | 295 | 0 | .992 | .990 | .985 |
| 1.986 (0.0682) | 196 | 0 | .989 | .985 | .977 |
| 3.1852 (0.1254) | 93 | 0 | .976 | .969 | .952 |

TABLE VI

CUMULATIVE PROBABILITY OF DETECTION STEEL MAGNETIC PARTICLE

| Flaw Size Greater than in mm (inches) | Cumulative Number of Observations | Cumulative Number of Misses | Probability of Detection at Confidence 90% | 95% | 99% |
|---|---|---|---|---|---|
| .8204 (0.0323) | 215 | 12 | .917 | .910 | .894 |
| 1.099 (0.0433) | 203 | 8 | .936 | .929 | .914 |
| 2.004 (0.0789) | 177 | 2 | .970 | .964 | .953 |
| 3.0048 (0.1183) | 91 | 2 | .942 | .931 | .908 |

TABLE VII

INFLUENCE OF STRUCTURAL QUALITY FACTOR ON P(B/A)
WITH A 5% and 0.5% ERROR PROBABILITY RATIO

| | Error Probability Ratio | |
|---|---|---|
| | 5%/.95 | 0.5%/.95 |
| | 0 | 0 |
| 99 | .16 | .66 |
| 70 | .21 | .73 |
| 50 | .28 | .79 |
| 19 | .51 | .91 |
| 9 | .68 | .955 |
| 3 | .86 | .985 |
| 1 | .95 | .995 |
| 0.3 | .985 | .999 |
| 0 | .100 | 1.00 |

TABLE VIII

INFLUENCE OF % FALSE INDICATIONS ON A 90%
PROBABILITY OF DETECTION FLAW SIZE FOR A GIVEN QUALITY FACTOR

≈ 10

| % Flase Indications | P(B/A) | Actual Probability of Detection of NDI in that Flaw Size |
|---|---|---|
| 0 | 1 | .90 |
| .1 | .989 | .88 |
| .2 | .978 | .88 |
| .5 | .947 | .85 |
| 1 | .900 | .81 |
| 5 | .640 | .57 |
| 10 | .470 | .42 |

AT 95% PROBABILITY OF DETECTION FOR A GIVEN FLAW SIZE

| | | |
|---|---|---|
| 0 | 1 | .95 |
| .1 | .989 | .939 |
| .2 | .979 | .930 |
| .5 | .950 | .90 |
| 1 | .904 | .85 |
| 5 | .665 | .63 |
| 10 | .487 | .46 |

TABLE IX

ACTUAL PROBABILITY OF FLAW BEING DETECTED

(TI PENETRANT) vs FLAW SIZE BY TWO INSPECTORS

INSPECTOR I FINDS 36% FALSE INDICATIONS, II FINDS 6%

= 10

| FLAW SIZE mm | FLAW SIZE inches | P(A/B)* | Inspector I | Inspector II |
|---|---|---|---|---|
| less than 0.635 | less than 0.025 | .34 | 2.9% | 12% |
| 0.635-1.27 | 0.025-0.050 | .59 | 8.3% | 29% |
| 1.27-2.54 | 0.050-0.10 | .88 | 17.6% | 52% |
| 2.54-6.35 | 0.10-0.25 | .94 | 19.4% | 57% |
| 6.35-12.7 | 0.25-0.50 | .93 | 19% | 58% |

*at a 95% Confidence Level

Figure 1

VENN DIAGRAM

For Conditional Probabilities
of Flaw Detection

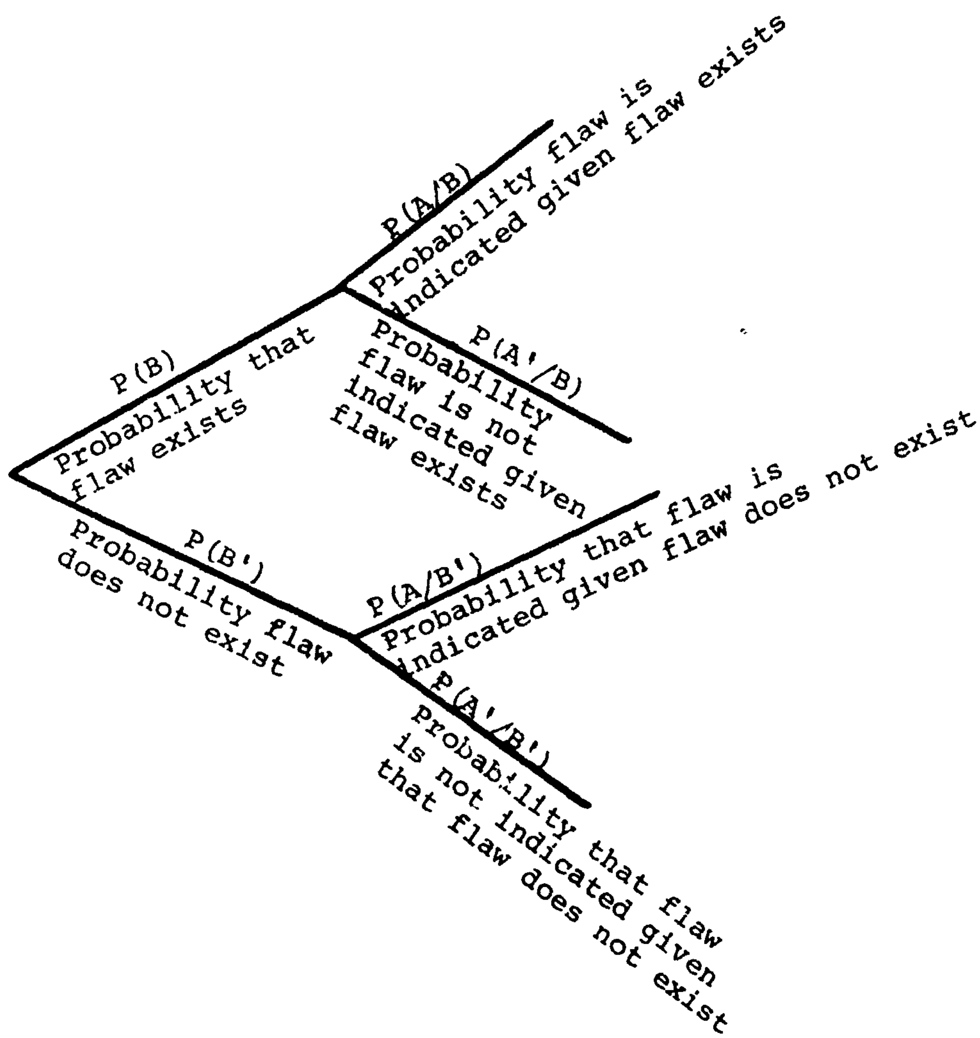
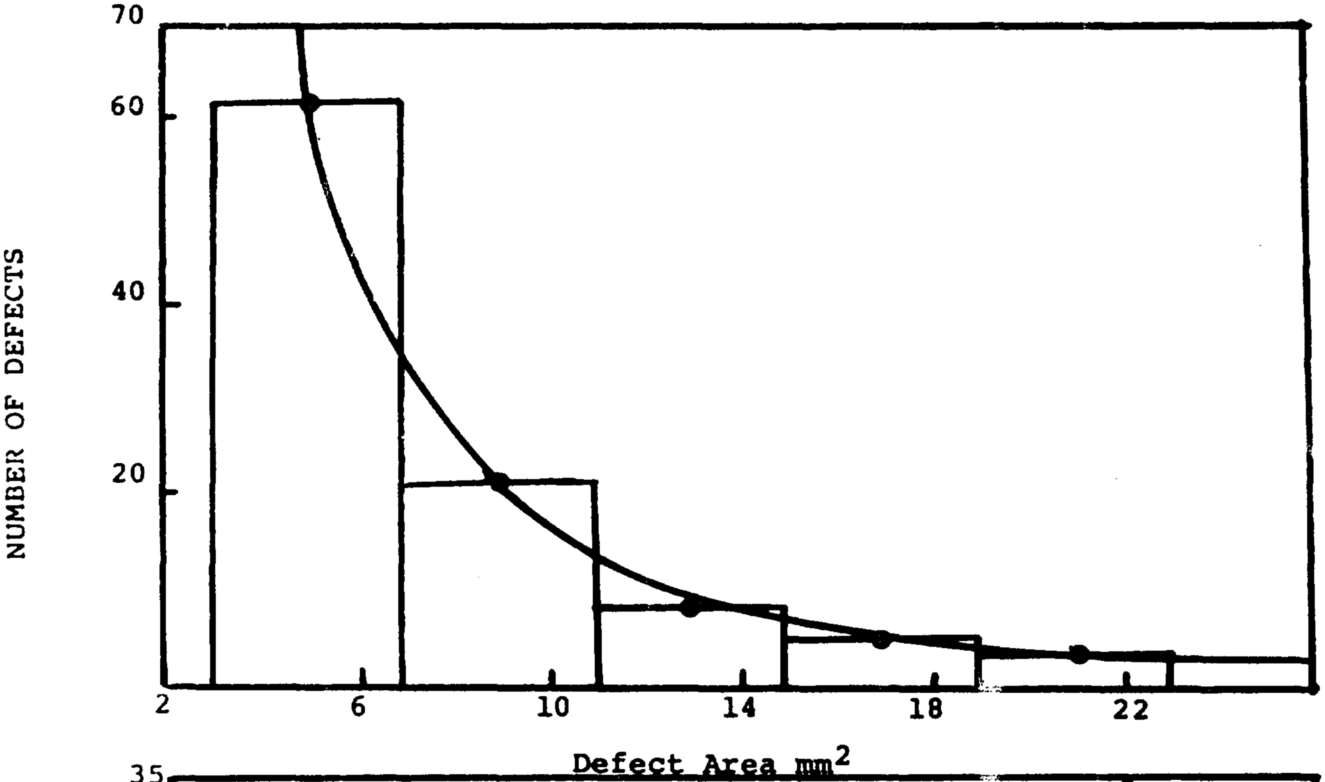
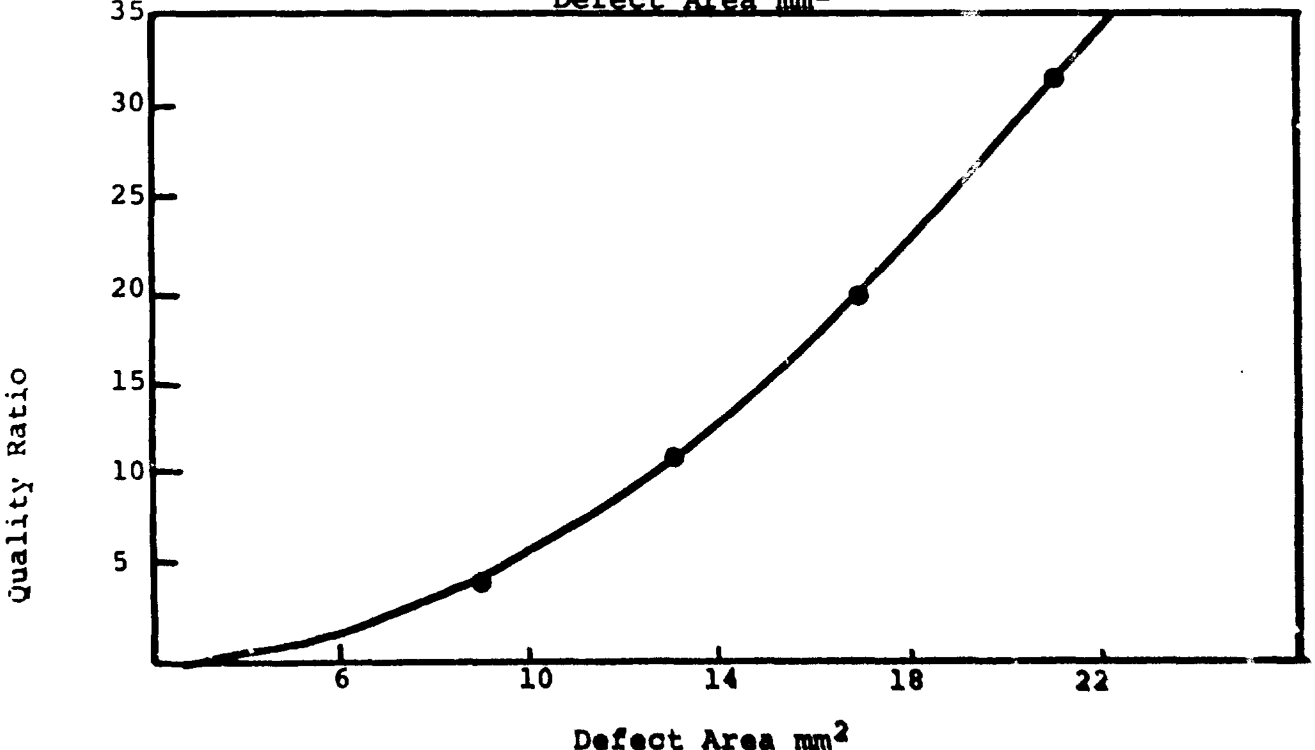


Figure 2

(Top) Size Distrubution of Defects in Aluminum Alloy Forging by Metallographic Analysis After Fel'dman (1968)




(Bottom) Quality Ratio as a Function of Defect Size for the Same Aluminum Alloy

Figure 3